Immersion lithography at 157 nm

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We present a preliminary study on the feasibility of immersion lithography at 157 nm for patterning below 70 nm. This technology can enable an enhancement in resolution of ~40% without radical changes in lasers, optics, or resist technology. We have identified a class of commercially available liquids, perfluoropolyethers, which are good candidates for use as immersion liquids. They are transparent ($\alpha \approx 10^{-3} \ \mu m^{-1}$ base 10), optically clean, chemically inert, and compatible with at least some current resist materials and with the semiconductor manufacturing environment. We have also constructed a high-resolution lensless interference immersion lithography system, preserving much of the design of a previous nonimmersion interference system. With this immersion interference tool, we have patterned resist with 30 nm dense features. © *2001 American Vacuum Society.*
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I. INTRODUCTION

Photolithography has been the mainstay of semiconductor device patterning for the last 2 decades and is expected to continue in a critical role at least to 70 nm and possibly beyond. Three trends developing in parallel have enabled this remarkable progress: (1) reduction in wavelength from mercury *g* line (436 nm) to the 193 nm excimer laser and further to the 157 nm and extreme ultraviolet wavelengths currently under development; (2) increase in the numerical aperture (NA) of projection systems from ~0.35 to over 0.7, with 0.8 expected in the next few years as the result of increasingly sophisticated optical designs, manufacturing techniques, and metrology; and (3) implementation of resolution enhancement techniques such as phase shifting masks and off axis illumination leading to a reduction in the k_1 factor from ~0.6 to values approaching 0.4.

Consideration has also been given to a more radical approach to improving resolution, immersion lithography[1-4] in which the space between the final optical element and the substrate is filled with a high index medium. In analogy with immersion microscopy, this has traditionally been understood to improve resolution by increasing NA, NA $\equiv n \sin \theta_0$, where θ_0 is the angular half aperture of the lens. While this plugs directly into the well known Rayleigh equations to give the correct resolution, it understates the depth of focus. The equivalent formulation[5] of an effective wavelength

$$\lambda_{\mathrm{eff}} = \lambda_0 / n, \tag{1}$$

where λ_0 is the vacuum wavelength and n is the index of the immersion medium, gives a resolution

$$W = k_1 \frac{\lambda_{\mathrm{eff}}}{\sin \theta_0} \tag{2}$$

and depth of focus (DOF)

$$\mathrm{DOF} \propto \frac{\lambda_{\mathrm{eff}}}{\mathrm{NA}_0^2}, \tag{3}$$

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where $\mathrm{NA}_0 = \sin \theta_0$ is the "dry" numerical aperture of the lens.

Immersion lithography has previously been demonstrated[1] at wavelengths as low as $\lambda_0 = 257$ nm with $n = 1.5$ or $\lambda_{\mathrm{eff}} = 171$ nm. However, to be of interest for semiconductor manufacturing, it must provide resolution beyond current or soon to be available conventional techniques. A system with $\lambda_0 = 157$ nm and $n = 1.37$ such as we present here has an effective wavelength of 115 nm, a larger gain than the transition from 193 to 157 nm, and should enable projection imaging with dense features as small as 50 nm for $\mathrm{NA}_0 = 0.9$ and $k_1 = 0.4$. Because the vacuum wavelength remains unchanged, much of the work on sources, optical materials and designs, resists, contamination control, etc., already done for 157 nm lithography translates directly to immersion lithography, greatly reducing the effort required to implement it. In this article we present data on immersion fluids for 157 nm lithography as well as initial results from our prototype immersion interference lithography system capable of patterning line and space features with spatial period $\Lambda = 60$ nm.

II. INDEX MATCHING MEDIUM

The first step in implementing immersion lithography at 157 nm is the identification of a suitable immersion fluid. Such a fluid must be transparent enough to allow a working distance of at least 10's of μm, must be free of optical defects, and must not interact with the resist to impede image formation. In addition, it must be compatible with the clean room environment and the semiconductor manufacturing process as well as be nontoxic and chemically inert. Ideally, the liquid should also be index matched to CaF_2 optics (i.e., $n = 1.56$) and resistant to laser damage. We have identified a class of commercially available materials, perfluoropolyethers (PFPEs), which satisfy many of these requirements and are certainly adequate for these initial studies. PFPEs are widely available as oils and lubricants, for example under the trade name Fomblin® (Ausimont Corp.). We have tested samples of two different PFPE materials, Fomblin Y and Fomblin Z (Fig. 1). Unless otherwise noted, tests were carried out on the Y-18 and Z-25 grades as received.
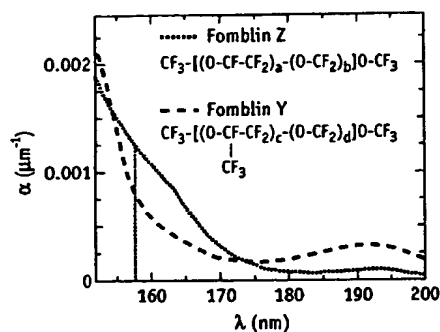
FIG. 1. Absorbance of the unirradiated perfluoropolyether compounds Fomblin Y and Z as a function of wavelength. In addition to the presence of a CF_3 side chain in Fomblin Y, these compounds differ in the ratio of their constituents: $a/b = 0.5-2$ while $c/d = 20-1000$.

The most important characteristic of an immersion fluid is its transparency. Measurements of the transmission of liquid layers of various thicknesses sandwiched between two CaF_2 windows yield the absorbance shown in Fig. 1. Both grades of Fomblin have 157 nm absorbance $\alpha_{157} \approx 10^{-3}$ μm^{-1} base 10 which is $\sim 1000\times$ lower than current experimental 157 nm resists[6] and $\sim 10\times$ lower than 157 nm pellicle materials.[7] This allows a working distance on the order of 50 μm with $\sim 90\%$ transmission. In addition, the shoulder of the absorbance curve appears just above 157 nm, leading to the hope that chemical modification could move it below 157 nm, yielding a fluid with dramatically lower absorbance. The optical quality of these fluids is also good. Figure 2 shows the far field scattering of light transmitted through a 50 μm layer of fluid between two CaF_2 windows. Fomblin Y contributes negligible scatter to that of the baseline empty cell while the additional scatter from Fomblin Z is roughly equivalent to 5 nm of surface roughness.

The resistance of the fluids to laser damage is illustrated in Fig. 3. A 150 μm thick layer of each fluid was irradiated at 157 nm. Fomblin Z is more damage resistant, with a 157 nm transmission drop of 17% for a dose of 100 $J cm^{-2}$ at a fluence of 0.3 $mJ cm^{-2} pulse^{-1}$. For the same dose, the trans-

FIG. 3. Transmission spectrum of a 150 μm layer of Fomblin Y (top) and Z (bottom) between two CaF_2 windows after various doses of 157 nm irradiation.

mission of Fomblin Y, which is initially higher, drops over 80%. The damage to either fluid in the dose required to expose a single field, ~ 1 $mJ cm^{-2}$, is negligible. However, the damage resistance of the fluid will influence its handling. An easily damaged fluid would likely travel with the wafer, providing a fresh volume for each exposed field. On the other hand, a damage resistant fluid could remain in the exposure tool, being replenished only as it is consumed.

The indices of refraction of Fomblin Y and Z, as determined by spectroscopic ellipsometry, are shown in Fig. 4 with $n_{157} = 1.35$ and 1.37 for Fomblin Z-25 and Y-18, respectively, and 1.38 for Fomblin Y-140, a higher molecular weight version. While this is not as high as might be desired, we envision that suitable chemical modification could increase this index and thus improve the resolution of immersion lithography. In addition, as pointed out in Ref. 1, the index mismatch between the CaF_2 final optic and the fluid leads to undesirable reflections. However, as in conventional lithography where the index mismatch is even greater, these reflections can be eliminated with a suitable coating on the final optic.
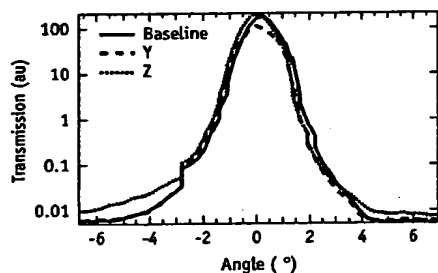

FIG. 2. Far field scattering of a cell consisting of 50 μm of immersion liquid (Fomblin Y or Z) sandwiched between two CaF_2 windows. The baseline is a cell with 50 μm of N_2 between the windows. Fomblin Y shows negligible scattering while Fomblin Z has scattering roughly equivalent to a 5 nm surface roughness. The sharp kink at $-2.75°$ is an artifact of the measurement.
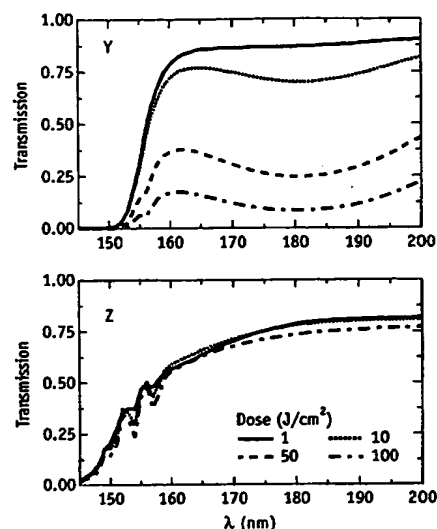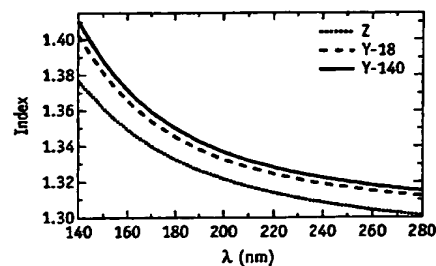

FIG. 4. Index of refraction of two Fomblin compounds at three molecular weights determined by spectroscopic ellipsometry.
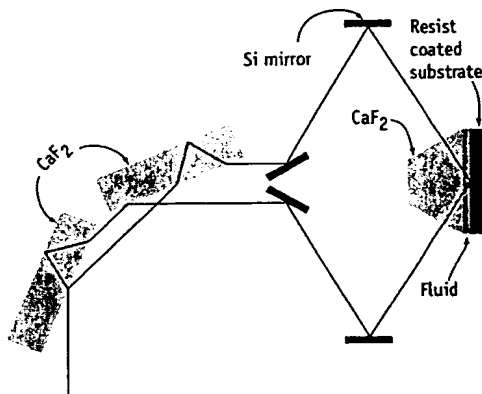
Finally, PFPEs have the advantage of being relatively chemically inert, nontoxic, and noncorrosive and thus compatible with the clean room environment and the semiconductor manufacturing process. Indeed, Fomblin is already present as pump oil in many clean rooms. We are currently studying the possible interactions of Fomblin with experimental 157 nm photoresists. For at least one resist, LUVR 99071, an ESCAP type resist[8] formulated for tool testing at 157 nm, it is clear that exposure to PFPEs neither swells nor dissolves the resist. Further studies are necessary to elucidate its impact, if any, on the imaging properties of the resist.

III. EXPOSURES

The initial immersion lithography platform is a high resolution lensless interference lithography tool similar to the dry tool described in Ref. 9. In interference lithography, two mutually coherent beams intersect at the surface of a resist coated substrate forming a line and space pattern with a spatial period

$$\Lambda = \frac{\lambda_0}{2n \sin \theta}, \tag{4}$$

where 2θ is the angle of intersection of the beams in air. In our design, $\theta = 60°$. This design was chosen for its ease of implementation with no mask, coatings, or curved optics, and its ease of adaptation to immersion lithography. A schematic of the optical path is shown in Fig. 5 which differs from the dry system in Ref. 9 only by the addition of the final CaF_2 trapezoid and immersion fluid. We emphasize that immersion lithography is in no way limited to interference lithography; we have simply chosen an interference system for its ease of implementation. While more complicated exposure systems will certainly require more extensive modifications for use in immersion lithography, this system dem-
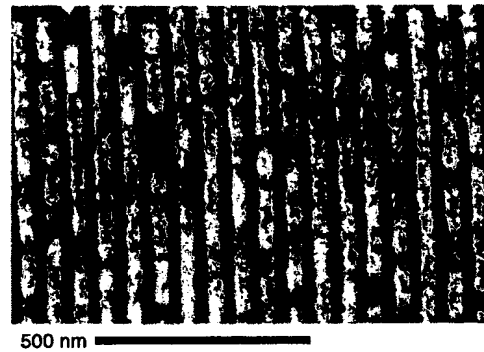

FIG. 6. SEM of a thin layer of LUVR 99071 resist exposed in the immersion interference lithography system.

onstrates both the potential for immersion lithography at 157 nm and the possibility for easy conversion of existing "dry" designs.

As pointed out in Ref. 1, it is the index of the final optic itself rather than that of the index matching fluid which decreases the spatial period of immersion interference lithography [Eq. (4)]. This can be understood by noting that a change in the index of the fluid will change both the effective wavelength and $\sin \theta$ by a factor of n, leaving Λ unchanged. The liquid thus serves only to allow the beams to exit the final optic at high θ without being totally internally reflected. In projection imaging, however, the ultimate resolution is set by the fluid index which determines the critical angle at the optic–fluid interface (or the fluid–resist interface if $n_{fluid} > n_{resist}$) and thus the largest possible intersection angle θ.

Thin layers (~ 55 nm) of LUVR 99071 resist[8] were spun on hexamethyl disilizane treated Si substrates and baked at 130 °C for 60 s. The substrate was then covered with a thin layer of immersion fluid and brought to within 50 μm of the CaF_2 trapezoid. After exposure, the sample was soaked for 3 min then rinsed in Fomblin PFS-1, a low molecular weight PFPE solvent, to remove the immersion liquid. This was followed by the standard 90 s postexposure bake (PEB) at 130 °C and 15 s soak in 0.26 N tetramethyl ammonium hydroxide developer. The scanning electron micrograph (SEM) of an exposure is seen in Fig. 6 showing a line and space pattern with $\Lambda = 60$ nm, as expected from Eq. (4) with $n = 1.56$ for the CaF_2 prism.

IV. SUMMARY

Immersion lithography is a possible path for extending optical patterning toward the 50 nm node while conserving much of the optical materials, resist, and other technology developed for dry 157 nm lithography. In this initial study, we have identified and characterized candidate immersion fluid materials. We have also demonstrated dense patterning with 30 nm feature size using immersion interference lithography. Much further work is clearly needed in many aspects of immersion lithography to understand its benefits and the

challenges it faces as well as the challenges of sub-100 nm lithography in general.

ACKNOWLEDGMENTS

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